THESIS REPORT ON PRACTICAL ASPECT OF POWER BUDGET AND QoS ANALYSIS OF WDM NETWORK

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CERTIFICATE

This is to certify that the thesis entitled "**Practical Aspect Of Power Budget and QoS Analysis of WDM Network**" submitted by **Manish Kumar Agarwal** and **Khumukcham Rajeshwar Singh** in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in **Electronics And Communication Engineering** at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my guidance during session 2010-2011.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any University /Institute for the award of any Degree or Diploma.

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Abstract - Optical fibre communication systems are composed of optical source, the optical fibre as transmission medium with associated connectors, and the photo detector with its associated receiver. The system designer must select from a set of device components to meet a given set of system requirements. We need to analyse, simulate and finally validate that the designed system satisfies those requirements. An important problem in WDM network design is to construct an algorithm to determine the optimal light-path from a set of all possible paths in a network topology. To establish an optical path, it is necessary to determine the route by which the call will traffic on and the wavelength that will be used on all links along the route. Based on the power budget and quality of service (QoS) analysis, we proposed a method of optimal light-path selection mechanism. The selected light path shows it's QoS in terms of Quality Factor (Q-factor).

Index Terms-

- **Launch Power**: This is the amount of the light energy as it leaves the fiber transmitter. This energy level is typically measured in decibels with respect to 1mW signal.
- **Receiver Sensitivity**: This is the minimum energy required for the fiber receiver to detect an incoming signal. This energy level is also measured in decibels with respect to 1mW signal.
- **Fiber Budget**: It is defined as the difference between the receive sensitivity from the Launch Power, which is in decibels (dB).
- **Attenuation**: Reduction of signal strength as it transmits from source to destination. Attenuation is the inverse process of amplification. Signal attenuation should not be too much; otherwise large number of repeaters will be requiredafter some distance. Attenuation is measured in decibels.

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CHAPTER 1

INTRODUCTION

Day to day growth in telecommunication network needs functionalities like dynamic data-path selection with guaranteed quality of service, which are essential for any optical network. At the present times, telecommunication networks still experience tremendous amount of traffic. In order to cope with traffic growth, telecom operators turned to optical fibre as a transmission medium having huge capacity in terms of bandwidth. Wavelength Division Multiplexing (WDM) in optical networks has made possible high throughput backbone networks. In deploying a WDM network based on dynamic light-path allocation, we have to take into consideration the physical topology of the WDM network and the traffic requirements. The physical topology is defined by the *nodes*, typically computers that generate data to be transmitted or computers where data is needed, the optical routers that determine how the optical signals are sent towards their respective destinations, and the fibre connections that provide the physical medium for communication. We have considered power-budget and finally computed Q-Factor, which is used for the selection of a light-path for a set of applications. The main objective is to select the best light-path from a number of all possible light-paths. The selection criteria are dependent on the Q-Factor parameter for every light-path in between the source and destination pair.

1.1 WDM NETWORK

In fibre-optic communications, wavelength-division multiplexing (WDM) is a technology which allows multiple optical carrier signals to be transmitted on a single optical fibre by using different wavelengths (colours) of the light to carry different carrier signals. This enhances the capacity of the optical fibre. In addition it enables bidirectional communications over single fibre.

A WDM is basically a fibre optical transmission technique, which multiplex signals of different wavelengths and provides data capacity in hundreds of gigabits per second over thousands of kilometres in a single mode fibre. As WDM system uses optical fibres for data transmission, which is more secure compared with other data transmission systems e.g., satellite communication, from tapping (as light does not radiate from the fibre, it is very difficult to tap it), it also provides immunity to interference and crosstalk.

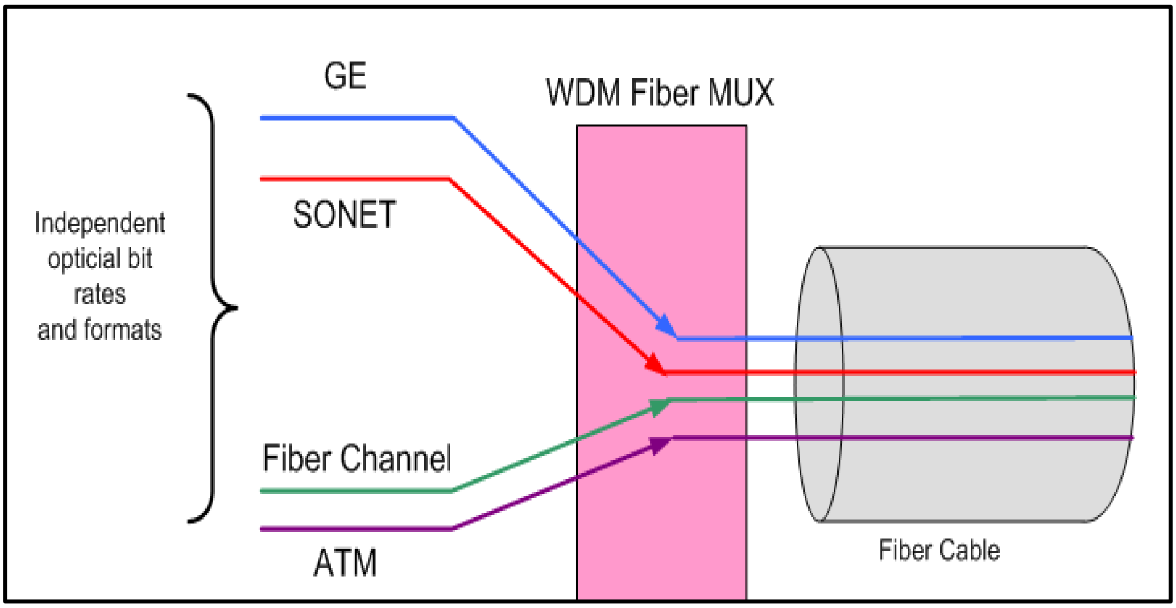


Figure 1.1 Wavelength Division Multiplexing

WDM systems are used in telecommunications, because they allow the system to expand the capacity of the network without laying more number of fibres. By using WDM and optical amplifiers, system can accommodate several generations of technology development in the optical infrastructure without having to improve the backbone network. Capacity of a given link can be increased by simply upgrading the multiplexers and demultiplexers at each end.

1.2 BENEFITS OF WDM

WDM technology allows multiple connections over one fiber thus reducing fiber plant requirement.

- This is mainly beneficial for long-haul applications and
- Campus applications which are used for cost benefit analysis.

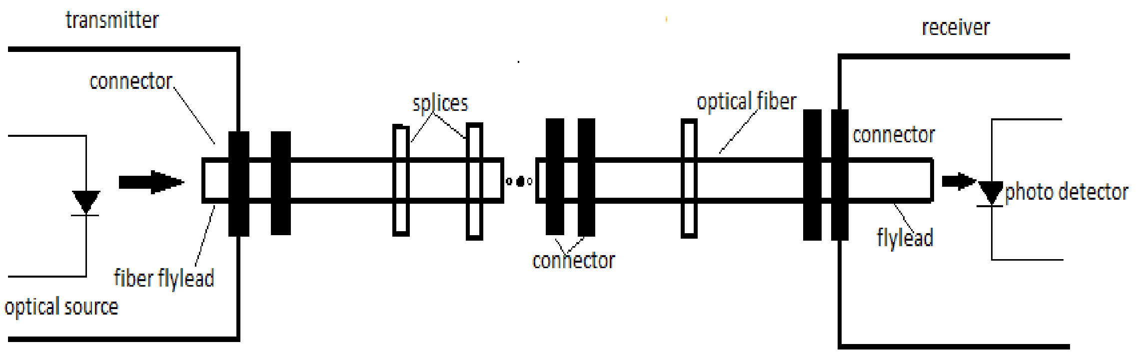
➢ WDM technology can also provide fiber redundancy.

➢ WDM provides a managed fiber service.

1.3 LINK LOSS MODEL

The optical power budget in a optical fibre communication link is the allocation of available optical power (launched into a given fibre by a given source) among various loss producing mechanisms such as coupling loss, fibre attenuation, splice losses, and connector losses, in order to ensure that adequate signal strength (optical power) is available at the receiver [3].

The link loss budget is derived from the sequential loss contributions of each element in the link. Each of these loss elements is expressed in decibels (dB).



Optical power loss model for a point-to- point link .
The losses occur at connectors,splices and in the fiber

Figure 1.3 Optical Link Model

In addition to the link loss contributors shown in the figure above, a link system margin is normally provided in the analysis to allow for component aging, temperature fluctuations and losses arising from components that might be added in future. A link margin of 6dB to 8dB is generally used for optical systems, which are not expected to have additional components incorporated in the future.

The amount of optical power launched into an optical fibre depends on the nature of optical source (like it is LED or LASER) and also on the fibre parameters like diameter, refractive index, orientation of fibre with respect to source.

Attenuation is the loss of optical power as light travels along the fibre. Attenuation in an optical fibre is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fibre material properties and fibre structure.

An optical fibre connector is a device that allows the coupling of optical power between two optical fibres or between two groups of fibres. It is difficult to design a device that allows for repeated fibre coupling without significant loss of light. Fibre optic connectors must maintain fibre alignment and provide repeatable loss measurements during numerous connections. Fibre optic connections using connectors should be insensitive to environmental conditions, such as temperature, dust, and moisture. Coupling loss is due to fibre misalignment, end preparation (extrinsic losses) and fibre mismatches (intrinsic loss). There is only a small amount of control over coupling loss resulting from fibre mismatches, because the loss results from inherent fibre properties.

Since performance and cost constraints are important factors in fibre optic communication links, the designer must carefully choose the components to ensure that the desired performance requirements in terms of the desired transmission distance, the data rate and the BER are maintained.

1.4 ATTENUATION AND ITS CAUSES

Attenuation causes reduction in signal strength or light power over the distance (length) of the light-carrying medium. Fibre attenuation is measured in decibels per kilometre (dB/km). Optical fibre offers better performance than other transmission media because it provides huge bandwidth with low attenuation. This allows signals to be transmitted over longer distances by using less regenerators or amplifiers, which reduces the cost and improves signal reliability.

Attenuation of a signal is a function of its wavelength. Attenuation in optical fibre is very low, as compared to other transmission medium (i.e., copper, coaxial cable, etc.), having a typical value of 0.35 dB/km at 1300 nm for standard single-mode fibre. Value of attenuation at 1550 nm wavelength is 0.25dB/km. This allows optical signal to be transmitted through fibre to travel more than 100 km without regeneration or amplification.

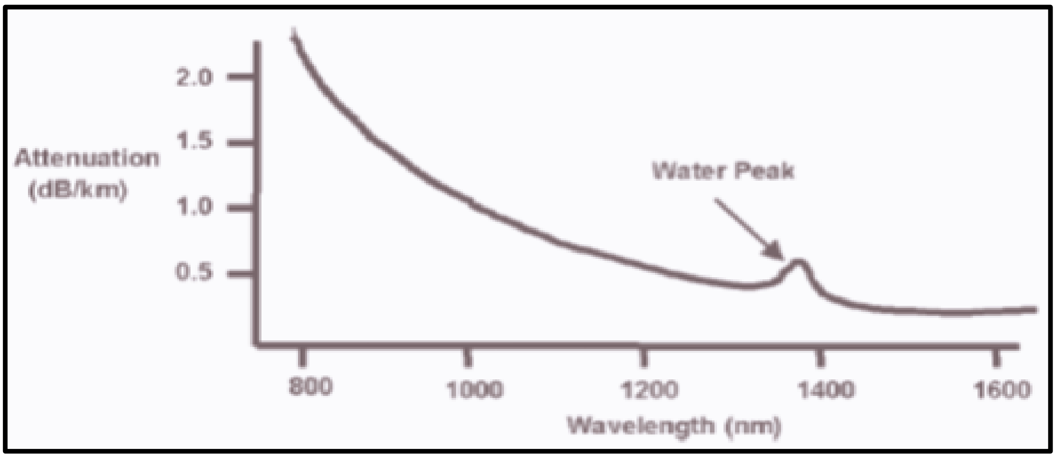


Figure 1.4 Attenuation as a function of wavelength

Attenuation is caused by different factors, but primarily it is due to **scattering** and **absorption.** The scattering of light is due to irregularities in molecular level in the glass structure which results to the general shape of the attenuation curve .Further attenuation is caused by light absorbed by residual materials, such as metals or water ions, within the fiber core and inner cladding. It is these water ions that cause the “water peak” region on the attenuation curve, typically around 1383 nm. The removal of water ions is of particular interest to fibre manufacturers as this “water peak” region has a broadening effect and contributes to attenuation loss for nearby wavelengths. Some manufacturers offer low water peak single-mode fibres, which increases the bandwidth and flexibility compared with standard single-mode fibres. Attenuation depends mainly on wavelength of light wave used.

The following equation defines signal attenuation as a unit of length:

$$\text{Attenuation} = \frac{10}{L} log_{10}\left(\frac{\mathrm{P_i}}{\mathrm{P_o}}\right) \tag{1}$$

Signal attenuation is a logarithmic relationship. Length (L) is expressed in kilometres. Therefore, the unit of attenuation is decibels/kilometre (dB/km). As previously stated, attenuation is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fibre-material properties and fibre structure.

As it evident from the **Figure 1.4,** attenuation constant mainly depends upon wavelength of optical carrier used. In WDM network different wavelengths are used for different user, which are passed through a single optical fibre so attenuation constant will be different for different user.

1.5 OTHER MAJOR LOSSES

Other than attenuation there are other major losses in optical fibre like coupling loss, splice loss and connector loss.

1.5.1 COUPLING LOSS

The relevant optical power is the amount of optical power that is coupled into the fibre. It depends on the following factors:

- The angles width over which the light is emitted
- The relative size of the source light-emitting area with respect to the fibre core size
- The alignment of the source with respect to fibre
- The coupling characteristics of the fibre (such as the NA and the refractive index profile)

1.5.2 SPLICE LOSS AND CONNECTOR LOSS

Connector and splice loss in optical fibre is caused by different factors, which includes lateral and axial misalignment that occurs when the axes of the two fibres are offset in a perpendicular direction and angular misalignment which occurs when the axes of two connected fibres are no longer parallel.

Coupling losses due to fibre alignment depend on fibre type, core diameter, and the distribution of optical power among propagating modes. Fibres with large numerical aperture reduce loss from angular misalignment and increase loss due to fibre separation. Multi-mode fibres are less sensitive to alignment errors than single-mode fibres because of their larger core size. However, alignment errors in multimode fibre connections may disturb the distribution of optical power in the propagating modes, which increases coupling loss.

1.6 POWER BUDGET

Power budget is the difference (in dB) between the transmitted Optical Power (in dBm) and the Receiver Sensitivity (in dBm). The power budget equation states that the power budget in a transmission system must equal the sum of all power losses in the system and the system margin.

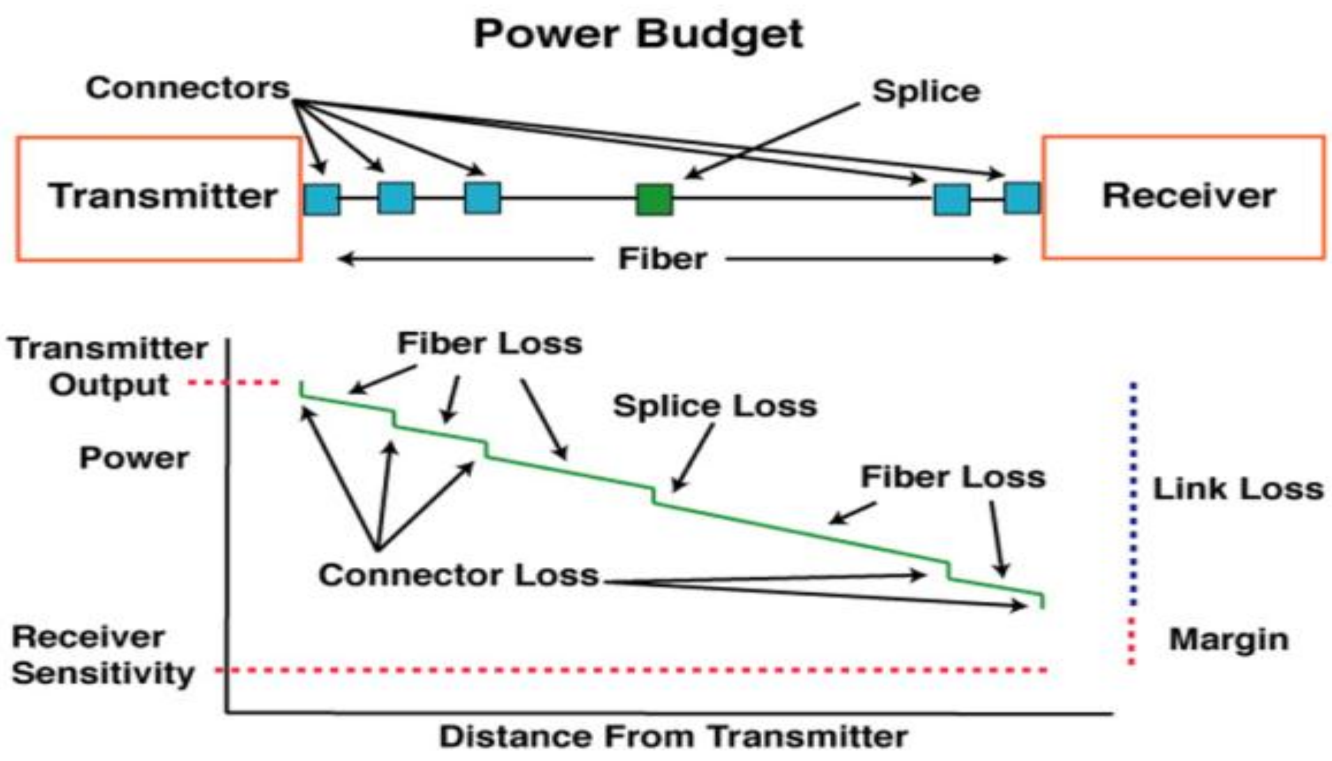


Figure 1.6 Graphical representation of power budget

So along the length of the fibre power gets decreased because of various losses which degrade the signal strength .Finally the power available at the receiver end should be greater than the minimum power required by the receiver (receiver sensitivity).

1.7 Q-FACTOR

Q-Factor of a light-path is defined as the ratio of output power relative to input power. It is normalised by dividing the value of Q-Factor with maximum value of Q-factor possible. It is expressed in percentage. So 100% Q-Factor means light-path has the highest Q-Factor and the light-path corresponding to this value of Q-Factor will be the best light-path.

To maximise the Q-Factor we need to maximise the output power for constant value of input power. We know that output power received is the attenuated version of input power due to attenuation loss, splice loss and connector loss. So we should try to minimise the losses in the optical fibre communication. Losses can be reduced by selecting the best components like connectors, splices and optical fibre which are having minimum power loss values. Out of all possible light-paths, the light-path having minimum power loss should be selected as optimal light-path.

1.7.1 KEY BENEFITS OF Q-FACTOR

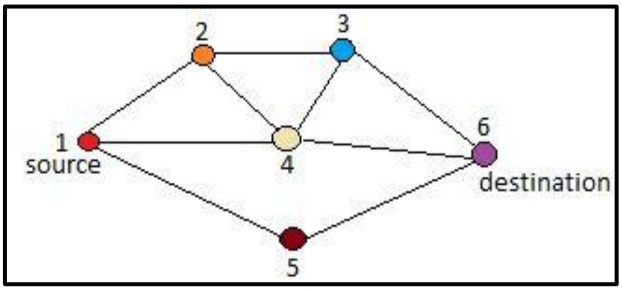
- It allows simplified analysis of system performance.
- Reflects the quality of the system without using difficult algorithm.
- It gives the cost in terms of power loss. Higher is the value of Q-Factor, better is the light-path of optical communication.
- It requires less time than other performance analysis method.

CHAPTER 2

SYSTEM MODEL

System may be modelled using nodes and links. System model gives the layout pattern of interconnections of the various elements like links, nodes, etc. of a network system. In a network, a node is a connection point, either a redistribution point or an end point for data transmissions. Nodes are represented by the coordinate system where the location of a node is given by point in a coordinate system. Link in a network is a connection through optical fibre link between two nodes. In a system link between too nodes is represented by the line joining between two nodes.

Connectivity in a system: Connectivity is determined by the connection between two nodes. If there is a link present between two nodes connectivity is taken as '1' otherwise it is taken as '0'. Using this connectivity matrix, light-path can be determined.



0	1	0	1	1	0
1	0	1	1	0	0
0	1	0	1	0	1
1	1	1	0	0	1
1	0	0	0	0	1
0	0	1	1	1	0

Figure 2.1 network topology **Figure 2.2 connectivity matrix**

Example: Let's consider a network system having 6 nodes as shown in Figure 2.1. In the given network topology, there is a link in between node1 and node2 so connectivity is taken as 1. Also there is no link in between node1 and node6 so it is taken as 0. Following the same we can find the connectivity matrix as shown in Figure 2.2.

2.1 PROBLEM FORMULATION

2.1.1 Power Budget Equation for Single link

Consider a fibre link pair (*i*, *j*) where *i* and *j* represents source and destination nodes respectively. P_t is the power launch from source node *i* into the fibre. Optical power produced by optical sources range from microwatts (μW) for LEDs to tens of mill watts (mW) for semiconductor Lasers. However, it is not practically possible to effectively couple all the available optical power from source into the optical fibre for transmission.

R_s is receiver sensitivity. Optical communication system uses a BER value to specify performance requirements. To achieve a desired BER a minimum average optical power value must arrive at the receiver end. This value is called receiver sensitivity.

α is the attenuation constant , L is length of fibre in between source and destination.

L_c is connector's loss which includes splices loss and N is the number of connectors used.

S_m is the system margin taken so that it will incorporate for component aging, temperature fluctuations and losses arising from components that might be added in future.

Using power budget equation [1], we can write

$$Pb(i,j) = P_t - R_s = \alpha * L + L_c * N + S_m \qquad (2)$$

So to find the power budget of an optical communication link, either both input and output power should be known or all kinds of losses occurring in the system should be known.

2.1.2 Power Budget Equation for Multiple links

In multiple-link communication network, each light-path from source to destination may consist of number of links. So in order to calculate power budget for a light-path from source to destination we have to consider power budget of each link present in that path. The overall power budget ($Pb_{overall}$) is given by summation of all the power budgets of the link present in that node. Mathematically

$$Pb_{overall} = \sum_{i,j \in p}^{n} Pb(i, j) \qquad (3)$$

Where, p € all possible light-path and (i, j) are node pair.

As for the case of power budget for a link, the overall power budget depends on attenuation constant, length of fibre in between source and destination, connector loss and number of connectors used.

Example: Consider the network topology in Figure 2.1.2

Suppose we want a communication from source node 1 to destination node 6. Light-path 1-2-3-6 is one of the possible light-paths from node1 to node6. Consider *Pb (1, 2)* = 10dB, *Pb (2, 3)* = 20dB and *Pb (3, 6)* = 30dB, the overall power budget using equation (3) will be 60dB.

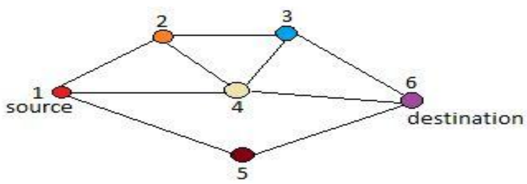


Figure 2.1.2 Network topology

2.1.3 Q-Factor of a light-path

Q-Factor is defined for a light-path as the ratio between output power and input power.

If P_{in} is the input power, P_{out} is the output power and Pb is the overall power budget of a light-path having multiple links, then we can propose to define Q-Factor (QF) as

$$\boldsymbol{QF} \quad = \frac{P_{out}}{P_{in}} = \frac{P_{in} - Pb}{P_{in}} \qquad (4)$$

So for the given value of input power Q-Factor can be calculated by calculating power budget of a light-path using equation (3). After finding the Q-Factor of all possible light-paths, we can determine the optimal light-path.

Example: Consider the system in Figure 7.2. Suppose we want to send optical signal from source node1 to destination node6. There are many possible light-paths as given below along with their overall power budget and QF.

Possible light-path	Power budget (in dB)	Q-Factor
1-4-2-3-6	4.16	6.53
1-2-3-4-6	3.48	7.10
1-2-4-3-6	2.80	7.66
1-2-3-6	2.93	7.55
1-2-4-6	2.95	7.54
1-4-3-6	2.23	8.14
1-4-6	2.38	8.01
1-5-6	1.12	9.07

As it is clearly evident that light-path 1-5-6 is the best light-path having maximum Q-Factor.

CHAPTER 3

ALGORITHM

3.1 ALGORITHM TO FIND ALL POSSIBLE LIGHT-PATHS

System is represented by using ‘n’ number of nodes and links are specified using line joining between nodes which is taken as ‘1’ if there is a connection between two nodes otherwise it is taken as ‘0’.

Notations: *St_node* = Start node, *End_node* = End node, *ptr* = Light-path

Step1. Find the *n*n* connectivity matrix for system having ‘n’ nodes using the method described.

Step 2. Input *St_node* and *End_node* from user.

Step 3. Initialize *Ptr* vector with *St_node* as its first element.

Step 4. For *i*= *St_node* find the non-zero elements of the i^{th} row of connectivity matrix.

Column nos. corresponding to that element will give next element of *Ptr* vectors.

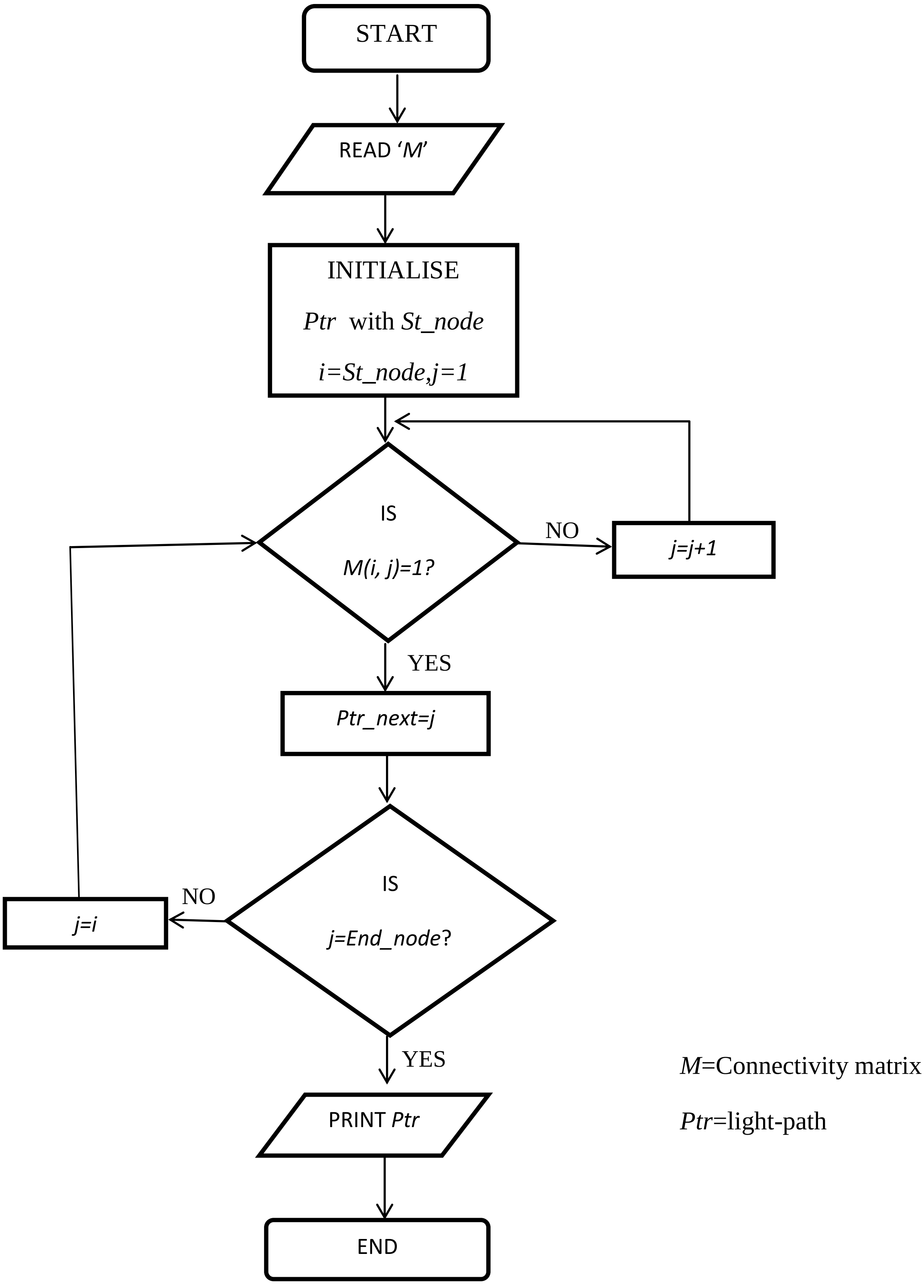
Step 5. For *j*=previous element, find column no. of the non-zero element in j^{th} row (say *k*).

If *k*≠any element of *Ptr* vector then nxt element is k.

Step 6. Repeat step 5 until *End_node* comes. *Ptr* vectors will give all possible light-paths.

The pointer vectors give all possible light-path from source node (*St_node*) to destination node (*End_node*).

3.1.1 Flow-chart



3.2 ALGORITHM TO FIND BEST LIGHT-PATH USING POWER BUDGET AND Q-FACTOR

STEP1: Calculate power budget for each link using the power budget equation (2).

STEP2: To find the overall power budget find the sum of power budgets of the links belong to the possible light-path using equation (3).

STEP3: Using the value of power budget calculated in STEP2 Q-Factor can be determined using equation (4).

STEP4: Repeat STEP2 and STEP3 to find total power budget and Q-Factor for each possible light-path.

STEP5: Find the maximum value of Q-Factor. Corresponding to this value of Q-Factor will give the best optimised light-path.

The above algorithm finds the best light-path from a set of all possible light-path using the concept of Q-Factor. To calculate Q-Factor, power budget is required. The light-path determined using this algorithm is optimal in the sense that it consumes least power.

CHAPTER 4

SIMULATION RESULTS

4.1 SYSTEM CONSIDERATIONS

In order to carry out link power budget analysis, we are required to decide which wavelength should be used to transmit and choose components accordingly. If the distance is small, we may decide to operate in the 770 to 910 nm region. But if distance is large, we should take the advantage of the lower attenuation and dispersion that occurs in the O-band through U-band region.

After decided the wavelength, it is required to find out the system performance of three major optical communication system building blocks; the receiver, the transmitter, and the optical fibre. The system parameters to select between a LED and a laser diode are data rate, transmission distance, and cost. Since lasers typically couple more optical power into a fibre than an LED, larger transmission distances without using repeater are possible with a laser but on the other hand LED is comparatively cheaper and has less complex circuitry than a laser. In choosing a particular photodetector, we mainly need to determine the minimum optical power that must fall on the photodetector to satisfy the BER requirement at the specified data rate. Also we need to consider cost and complexity constraints.

For selecting the optical fibre, we can either go for single-mode fibre or multi-mode fibre, and either of them can have a step or a graded-index core. LEDs are appropriate to use with multi-mode fibres. When choosing the attenuation characteristics of a cabled fibre, the excess loss that results from the cabling process must also be considered in addition to the attenuation of the fibre itself which includes connector and splice loss as well as environmental-induced losses that could arise from temperature variations, radiation effects, and dust and moisture on the connectors.

We have considered network topology as shown in Figure 2.1 having 6 nodes. The links are shown by the line joining between two nodes. The network topology considered has the connectivity matrix as shown in Figure 2.2. Also we have considered that there are communications between three pair of source and destination nodes which are (1,6), (1,4) and (6,4).

Following are the results for source node1 and destination node6, when above described algorithm is simulated using matlab.

power budget matrix

0	84.8590	32.0941	117.6051	76.4001	31.4097
84.8590	0	122.9008	89.8735	27.4957	192.1570
32.0941	122.9008	0	20.0395	71.2642	85.7027
117.6051	89.8735	20.0395	0	64.9613	120.0792
76.4001	27.4957	71.2642	64.9613	0	35.6561
31.4097	192.1570	85.7027	120.0792	35.6561	0

Figure 4.1.1 Power budget matrix

all possible paths

1	4	2	3	6	0
1	2	3	4	6	0
1	2	4	3	6	0
1	2	3	6	0	0
1	2	4	6	0	0
1	4	3	6	0	0
1	4	6	0	0	0
1	5	6	0	0	0

Figure 4.1.2 All possible light-paths

Light-path ref. no.	Possible light-path	Power budget (in dB)	Q-Factor
1	1-4-2-3-6	4.16	6.53
2	1-2-3-4-6	3.48	7.10
3	1-2-4-3-6	2.80	7.66
4	1-2-3-6	2.93	7.55
5	1-2-4-6	2.95	7.54
6	1-4-3-6	2.23	8.14
7	1-4-6	2.38	8.01
8	1-5-6	1.12	9.07

Table 4.1.1 Light-path and corresponding power budget and Q-Factor

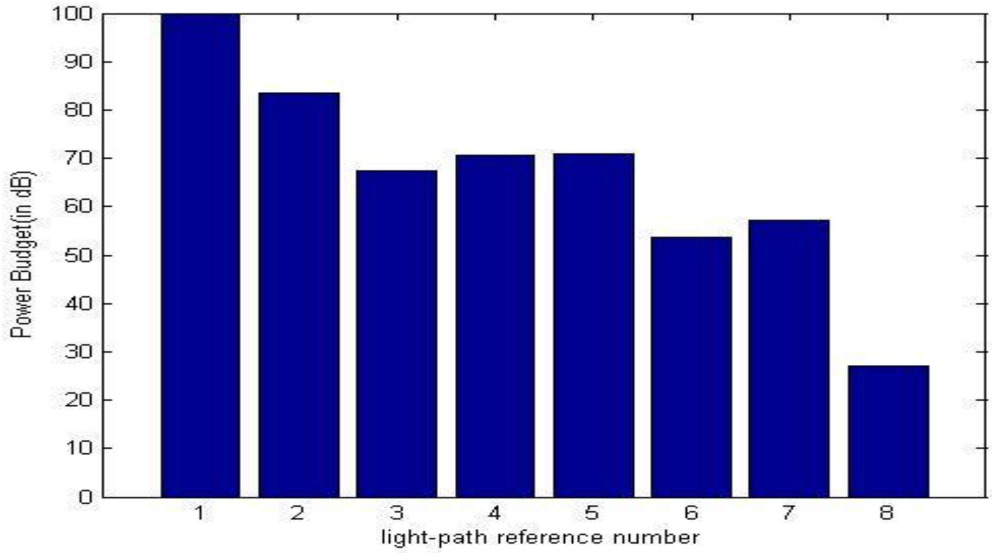


Figure 4.1.3 Graph of power budget vs. light-path reference number

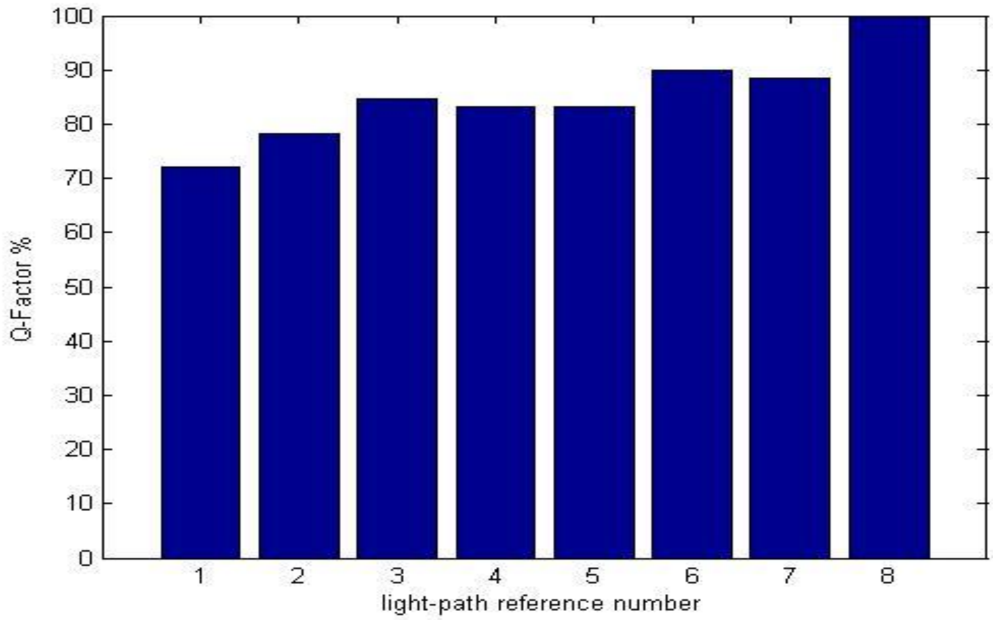


Figure 4.1.4 Graph of Q-Factor vs. light-path reference number

Graph in Figure 4.1.3 and Figure 4.1.4 shows the variation of power budget and Q-Factor with light-path reference number. From Q-Factor graph, light-path reference number 8 has the maximum Q-Factor. So light-path 1→5→6 having light-path reference number 8 is the optimal light-path.

Following are the results for source node1 and destination node4, when above described algorithm is simulated using matlab.

```
power budget matrix
         0   22.4851   51.1963   60.2838   41.6509  229.6111
   22.4851         0  116.5857   91.1344   62.2852   29.0834
   51.1963  116.5857         0   30.2494   98.4265   68.3487
   60.2838   91.1344   30.2494         0   36.4540   68.9430
   41.6509   62.2852   98.4265   36.4540         0  125.9886
  229.6111   29.0834   68.3487   68.9430  125.9886         0
```

Figure 4.1.5 Power budget matrix

```
all possible paths
     1     5     6     3     2     4
     1     2     3     6     4     0
     1     2     3     4     0     0
     1     2     4     0     0     0
     1     5     6     3     4     0
     1     5     6     4     0     0
     1     4     0     0     0     0
```

Figure 4.1.6 All possible light-paths

Light-path ref. no.	Possible light-path	Power budget (in dB)	Q-Factor
1	1-5-6-3-2-4	4.44	6.30
2	1-2-3-6-4	2.76	7.70
3	1-2-3-4	1.69	8.59
4	1-2-4	1.14	9.05
5	1-5-6-3-4	2.66	7.78
6	1-5-6-4	2.37	8.02
7	1-4	6.03	9.50

Table 4.1.2 Light-path and corresponding power budget and Q-Factor

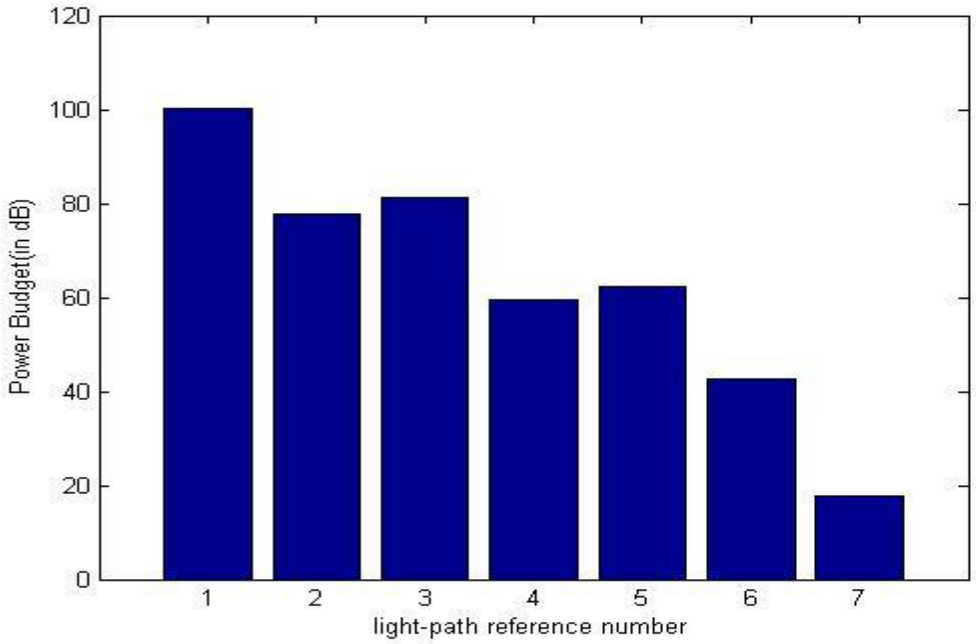


Figure 4.1.7 Graph of power budget vs. light- path reference number

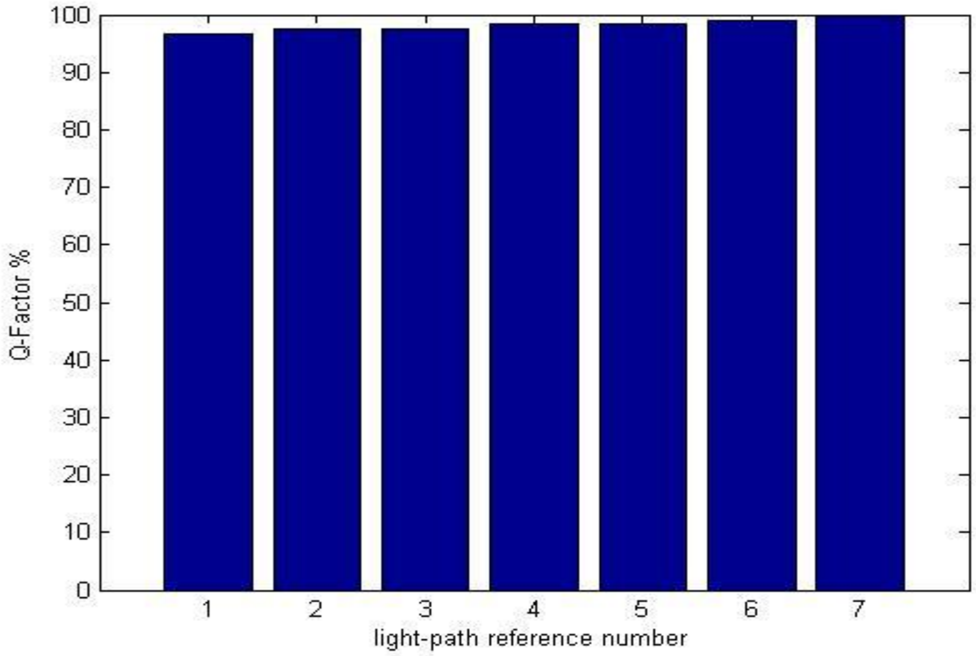


Figure 4.1.8 Graph of Q-Factor vs. light-path reference number

Graph in Figure 4.1.7 and Figure 4.1.8 shows the variation of power budget and Q-Factor with light-path reference number. From Q-Factor graph, light-path reference number 7 has the maximum Q-Factor. So light-path 1→4 having light-path reference number 7 is the optimal light-path.

Following are the results for source node1 and destination node4, when above described algorithm is simulated using matlab.

power budget matrix

0	25.4368	35.7992	30.6887	12.6136	160.4475
25.4368	0	91.4196	50.3514	74.2749	92.4676
35.7992	91.4196	0	82.1552	48.5441	25.6885
30.6887	50.3514	82.1552	0	71.5893	17.8485
12.6136	74.2749	48.5441	71.5893	0	16.4134
160.4475	92.4676	25.6885	17.8485	16.4134	0

Figure 4.1.9 Power budget matrix

all possible paths

6	5	1	2	3	4
6	3	2	1	4	0
6	5	1	2	4	0
6	5	1	4	0	0
6	3	2	4	0	0
6	3	4	0	0	0
6	4	0	0	0	0

Figure 4.1.10 All possible light-paths

Light-path ref. no.	Possible light-path	Power budget (in dB)	Q-Factor
1	6-5-1-2-3-4	2.28	8.10
2	6-3-2-1-4	1.73	8.56
3	6-5-1-2-4	1.05	9.13
4	6-5-1-4	5.97	9.50
5	6-3-2-4	1.67	8.60
6	6-3-4	1.08	9.10
7	6-4	1.78	9.85

Table 4.1.3 Light-path and corresponding power budget and Q-Factor

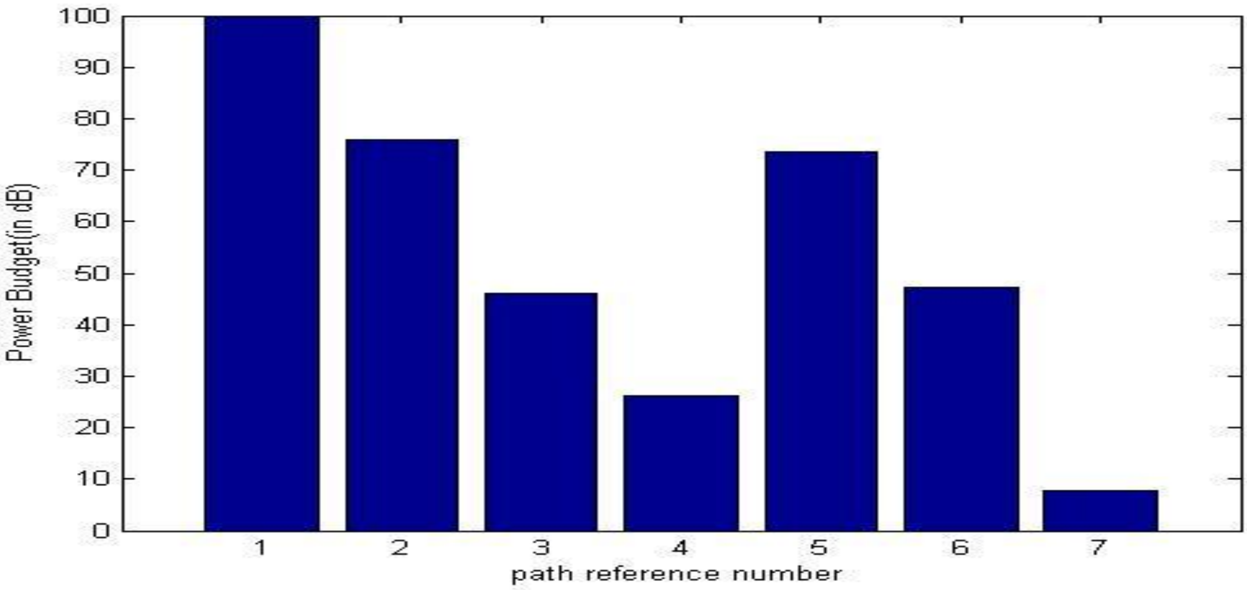


Figure 4.1.11 Graph of power budget vs. light-path reference number

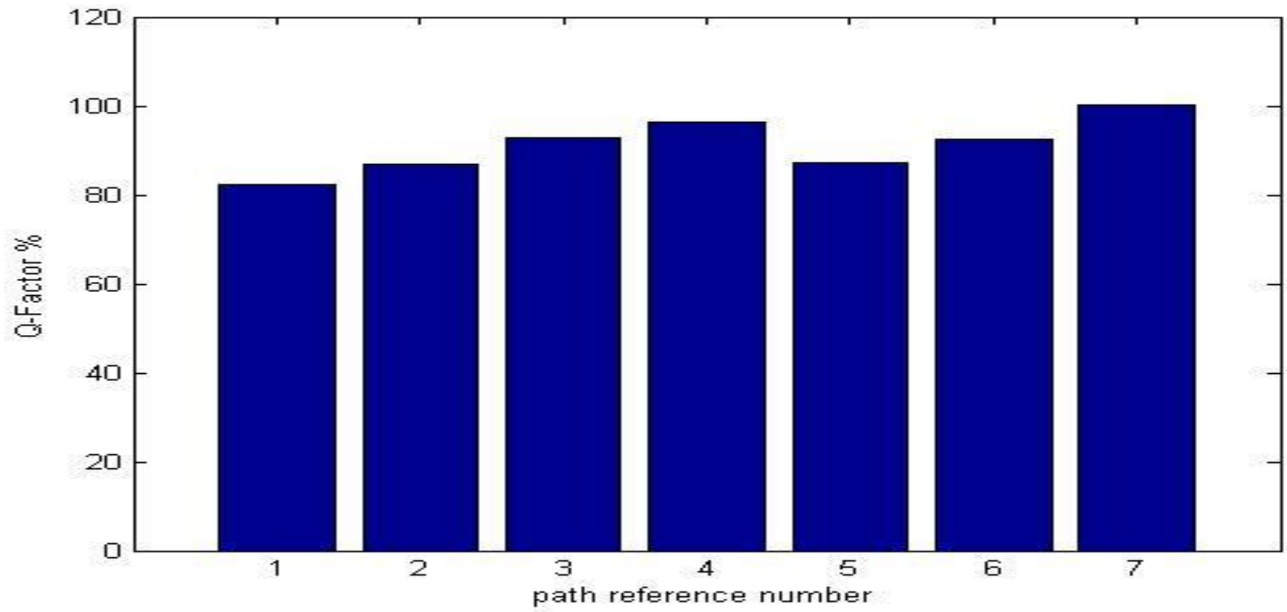


Figure 4.1.12 Graph of Q-Factor vs. light-path reference number

Graph in Figure 4.1.11 and Figure 4.1.12 shows the variation of power budget and Q-Factor with light-path reference number. From Q-Factor graph, light-path reference number 7 has the maximum Q-Factor. So light-path 6→4 having light-path reference number 7 is the optimal light-path.

CHAPTER 5

CONCLUSION

We have presented an algorithm that determines the best light-path from all possible light-paths to transmit a signal from source node to destination node with respect to the power budget and Q-Factor. This can be design for both single link and multiple link communication networks. The result shows the variation of power budgets and quality factor for various light-paths for different combination of source and destination pair.

Using this method, first we found all possible light-paths from source to destination. Then we calculated corresponding to each light-path, the power budget and Q-Factor. The algorithm described in this thesis to find the best light-path from all possible light-paths is simple to implement as we don’t have to convert signals in optical domain to electrical domain. Power can be directly related to cost function. The method we described will give the best light-path in terms of least power, so the cost function will be least for the best light-path computed using the algorithm described above.

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